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An initial exploration of spatial spreading of cascading failure in an electric power system

by

Lingyun Ding

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Electrical Engineering

Program of Study Committee:

Ian Dobson, Major Professor

James McCalley

Zhengdao Wang

Iowa State University

Ames, Iowa

2013

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DEDICATION

I would like to dedicate this thesis to my Mother for her continuous spiritual backing, and my Father for his strict education from my childhood.

Also I would like to dedicate this thesis to the decade of hard working in the State Grid of China (SGCC), the harsh and rigorous environment made me grow up independently and try my best to become the connoisseur of secondary system and to understand the whole power system deeply. Without the experience, it was definitely impossible for me to finish this research project, although the the difference between the structure of American power system and the one of China is very wide.

Furthermore, this thesis is sincerely dedicated to the Chinese ancient sages for their tolerance, integrity, honesty, self-discipline, modesty, rigorous attitude of scholarship and indifference to fame and wealth, which keeps on impacting me profoundly. Thanks for their noble characters supporting me to keep walking alone in the way of pursuing truth.

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ABSTRACT

Large blackouts typically involve the cascading outage of transmission lines. However, little is known about the overall patterns of cascading outages. This research processes and initially examines observed utility data to explore the spatial spreading of cascading failure. The utility data is combined from two different sources, one year of recorded transmission line outages and a description of the grid connections. This requires extensive work relating different descriptions of the same grid. An initial analysis of the statistics of the spreading is presented, and the potential and implications of a new statistical approach to cascade spreading is assessed.

CHAPTER 1. OVERVIEW

Power grids are the man-made systems that have the most extensive coverage and the most complex structures in the world as a pillar of the international economy. Therefore the safe operation of power grids is necessary for all countries. However, in recent years, large-scale blackouts around the world happened quite frequently. Scientists and engineers worked together to identify the reasons for major large-scale blackouts, yet in many cases convincing analytical results are still missing, and electrical blackouts keep recurring.

In 1996, after two large-scale blackouts took place in succession in the power grids of the western US, the North American Electric Reliability Corporation (NERC)[1] set up a new group working on the dynamics of interconnected power systems, and in particular studying topics of the system stability, voltage, reactive power, control and protection. The goal was to establish a set of standard procedures and principles to ensure proper planning and reliable operation of interconnected power systems. However, seven years later, on August 14, 2003, there occurred a blackout in US and Canada that shocked the world. Compared to the two blackouts in 1996, the losses of the August 14 blackout in US and Canada were much bigger. Unfortunately, the large-scale blackout that happened in California in 2010 and the blackouts that occurred in India last year shocked the whole world again. The reason why the blackout and cascading failure is hard to mitigate is rooted in the lack of an effective systematic study on the characteristics of power grid dynamics and the mechanism of large-scale blackouts.

Reference [9] pointed that due to the complexity of the structures and operation modes of power grids, researchers have not obtained sufficient knowledge about the nature of blackouts

[1] The North American Electric Reliability Corporation (NERC), a nonprofit corporation based in Atlanta, Georgia, was formed on March 28, 2006, as the successor to the National Electric Reliability Council (also known as NERC). The original NERC was formed on June 1, 1968, by the electric utility industry to promote the reliability and adequacy of bulk power transmission in the electric utility systems of North America.

in large-scale interconnected power systems which are caused by cascading failures. The existing theories and computational and experimental methods are limited in the following two aspects. First, since all the departments of power utilities function separately to manage the systems' planning, construction and operation, the problems about the long-term evolution of the systems are not considered as a whole. Second, the current $N-1$ and $N-2$ operational standards assume that cascading failures are small probability events, and that the impact of these incidents on system blackouts can also be ignored because of the small probabilities. However, it is evident now that these cascading failures can trigger blackouts of various scales. Statistical data have shown that the probability distribution of blackouts does not satisfy the normal distribution but a power-law distribution with a heavy tail. In other words, the risk of large-scale blackouts cannot be ignored. These facts indicate that it is necessary to establish appropriate models to study cascading blackouts, and then guide the planning and operation of power systems based on these models.

1.1 Introduction

In recent years, researchers have applied complex system theory and the related tools in computer science, ecology, sociology, economics and other related disciplines to the study of complex power grids about cascading failure. Cascading failure is a series of dependent failures that progressively weakens the system. Large electric power transmission systems occasionally have cascading failures that cause widespread blackouts, with up to tens of millions of people affected [2, 3, 4]. The many mechanisms involved in cascading outages are complicated and varied, but all cascades include transmission branch outages.

This thesis studies the spatial spreading behavior of cascading transmission branch outages from standard utility data that records the times of branch outages. The objective is to characterize the spreading statistically. The statistics of the spreading will be useful as reference data that can be used to validate models and simulations of cascading failure. It is also useful to be able to assess the chances of a cascade that starts in one region or utility to spread beyond the region boundaries.

Working with observed data on the graph of the networks of the utility to explore the mechanism of cascading failure spatial spreading is complementary to the size propagation of cascading failure studied previously [5, 6, 7]. The two approaches will offer different dimensions to study cascading failure in space and scale, and combining both of them we can understand cascading failure more clearly. Branching process models as a bulk statistical models of cascading failure has been used to represent cascading propagation successfully, while the study about the spreading statistical model of cascading failure by realistic power network has not, to our knowledge been addressed. We hope that a better understanding of the mechanism of spatial spreading of cascading failure can benefit reliability analysis, wide-area vulnerably assessment, local relay settings, and planning.

1.2 Literature Review

To reveal the mechanism for the cascading failures in power systems, different fault models have been proposed by analyzing both the macroscopic topological features and microscopic component characteristics; which can be classified into three categories [9].

1.2.1 Cascading failure models based on network topologies

These static models describe the macroscopic topologies of power grids. The typical examples include the betweenness centrality model [10, 11, 12] model [13, 14] and effective efficiency model [15]. These models do not represent the actual dynamical mechanism for the evolution of failures in the power grid.The main reason is that the power grid has been idealized in these models into a graph and the cascading only depends on topological concepts such as node degrees. It is assumed that the power flow between nodes always takes place through the shortest path between them or they define an effective path for the power flow and assume the load redistribution will depend on the adjacent path with higher effective efficiencies. Moreover, in the complex network area, it is widely thought that cascading failure will always spread to the adjacent branches in complex network area. But these assumptions are not verified in the real power grid. That is, these models reveal interesting properties of cascading failure on graphs, but do not yield conclusions about power systems.

1.2.2 High-level cascading failure models

1. The CASCADE model,[16, 17, 20] found that when the load levels increase to some critical values, the fault distribution exhibits the power-law tail characteristics and when load level keeps increasing, large-scale blackouts may happen. The CASCADE model is a high level model that can capture some features observed in blackouts qualitatively. But this model does not directly represent any features of the power system; it assumes that all the components and their interactions are identical and ignores the network topology.

2. Branching process model[5, 6, 7, 18] has been applied to predict the distribution of total number of outages for a given number of initial outages. This model is another high level model and it naturally approximates the CASCADE model.

1.2.3 Cascading failure simulations

The OPA model, Hidden failure model and Manchester model are representative models of this type, which all take into account power system power flows and their redistribution when there is an outage. Both DC OPA and the hidden failure model only consider active power and assume that the bus voltage is constant and assume that the transmission branch will trip when the power flow though it exceeds a pre-set threshold value. This is a very simplified model of the protection.[2] It is reasonable that AC OPA model and Manchester model are based on AC power flow considering both reactive power and voltage. Hidden failures contribute to cascading failure in that the primary protection cannot protect the branch, which results in the backup protection tripping the adjacent branch and then extending the outage area. However, hidden failures are less well understood [23, **?**], and it also depend on the configuration of the fleet of relays and improper artificial reasons or process faults etc..

Studying the spatial spreading of cascading failure with recorded utility data is a effective and scientific direction to understand the mechanism of cascading failure, which will help

[2] In fact, overload protection for branches is rarely used in the meshed high voltage part of the network. In power grid rated at 230 kV or above, a distance relay take the responsibility for the line protection considering the direction of power flow other than overload or over current relay without considering the direction, which is a very important rule in the setting of protection schedule. Also if distance relay can be activated, two criteria should be satisfied at the same time, one is the voltage value should decrease to the setting value and the current value should increase to the threshold.

to improve the existing simulation of cascading failures and hence get more effective defense against cascading failure and large blackouts.

1.3 Motivation Form a Real Big Blackout

An interesting example of how cascading failures spread is in Fig. 1.1 from the July 1996 blackout report [1]. Fig. 1.1 shows the numbered sequence of branch outages in the Northwest USA. The cascading failure does not only spread to the branches adjacent to the ones which tripped previously, although the spreading to the adjacent ones might be more likely than the non-adjacent ones. This thesis aims to statistically characterize the typical spreading in cascading outages so that such observations can be made with assurance.

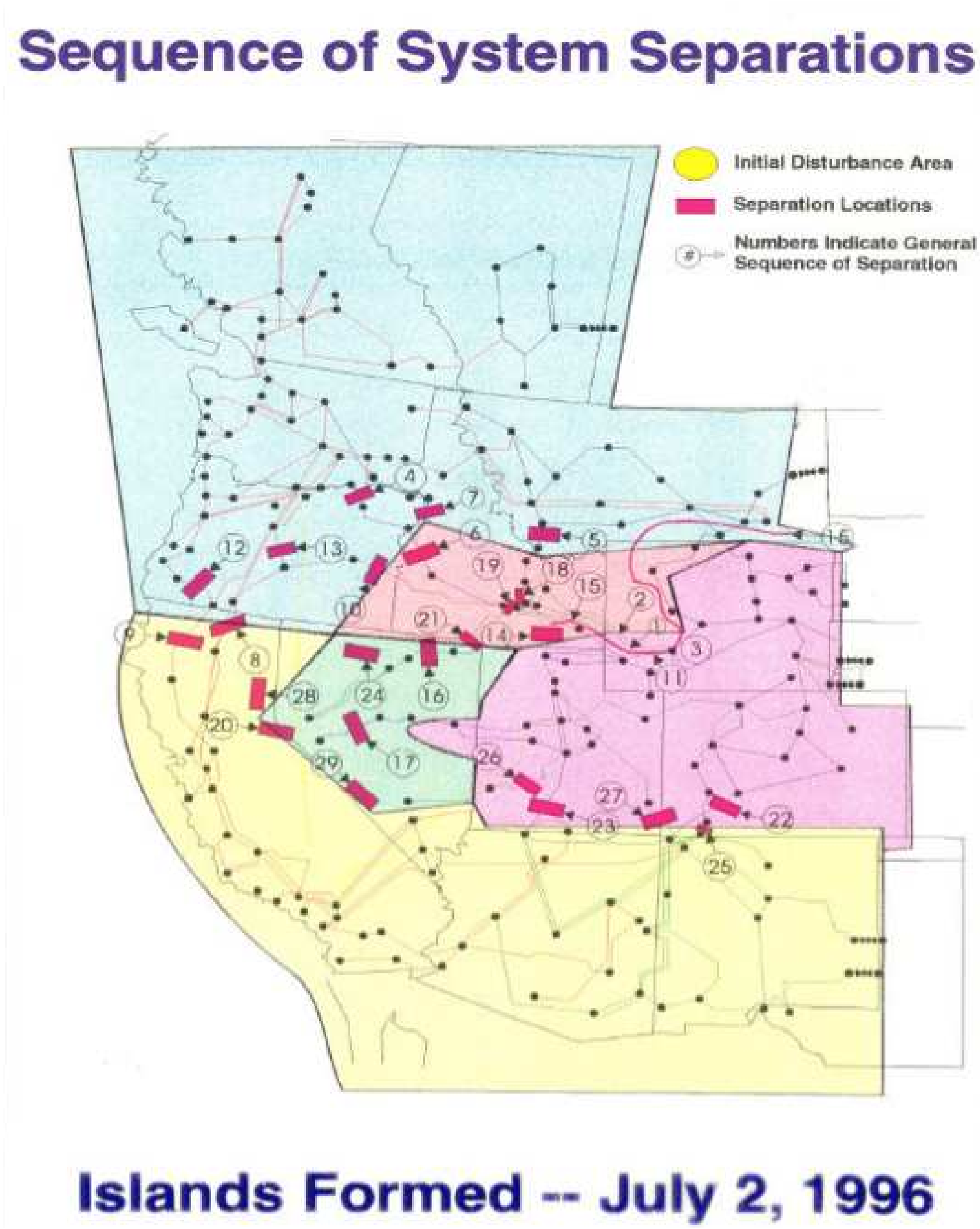

Figure 1.1 The Western area blackout of July 1996; the numbers show the sequence of outages; reprinted from [3]

CHAPTER 2. OBTAINING AN APPROXIMATE SUBGRID OF WECC THAT CONTAINS BPA

2.1 Utility data

The utility data studied in this research is combined from two different sources, one year of recorded transmission branch outages from the Transmission Availability Data System (TADS) data of BPA[1] and a description of the grid network of WECC[2] Western area power grid. The WECC network data describes the grid components in detail and their connections and is in PSSE[3] format.

In this research, the network topology is extracted from a WECC summer 2009 high load planning case grid model of approximately 16000 buses, 14,000 high and medium voltage transmission branches, and 6500 transformers. The voltage levels include 500 kV, 345 kV, 300 kV, 230 kV, 138 kV, 115 kV, etc., most of them are above 69 kV.

Transmission owners in the USA are required to report transmission branch outage data to NERC for the Transmission Availability Data System (TADS). The TADS data we studied is recorded by the North American utility BPA for the whole year of 2009, in which there are altogether 758 outages. The TADS data for each transmission branch outage includes the

[1] The Bonneville Power Administration (BPA) is an American federal agency based in the Pacific Northwest. BPA was created by an act of Congress in 1937 to market electric power from the Bonneville Dam located on the Columbia River and to construct facilities necessary to transmit that power. Congress has since designated Bonneville to be the marketing agent for power from all of the federally owned hydroelectric projects in the Pacific Northwest. Bonneville, whose headquarters are located in Portland, Oregon, is one of four regional Federal power marketing agencies within the U.S. Department of Energy (DOE).

[2] The Western Electricity Coordinating Council (WECC) is a non-profit corporation that exists to assure a reliable Bulk Electric System in the geographic area known as the Western Interconnection. This area includes all or parts of the 14 western United States, two Canadian provinces, and the northern portion of Baja California, Mexico.

[3] Power System Simulator for Engineering (PSSE) is a software tool used for electrical transmission networks. It is an integrated, interactive program for simulating, analyzing, and optimizing power system performance and provides probabilistic and dynamic modeling features. The software provides for transmission planning and engineers a tool for use in the design and operation of reliable networks.

outage time (to the nearest minute), voltage level, causes and components. All the branch outages are automatic trips. More than 52% of the outages are of branches rated 230 kV or above, the branches rated 500 kV account for 23.1%, the branches rated 345 kV account for 2.5%, the branches rated 287 kV account for 0.66%, and 25.9% of the outages are of branches rated 230 kV.

The voltage levels considered in this research are the ones above or equal to 230 kV. It is reasonable to omit some of the outages at a lower voltage level because they tend not to be in the meshed part of network that we wish to study. However, for simplicity for this initial study, we also omitted the 115 kV and 138 kV branch outages.

This chapter explains the need for choosing a subgrid of WECC that contains BPA and explains the steps to obtain the subgrid.

2.2 Introduction

For researching how cascades spread on the power grid, it is important to get the whole structure of the networks for tracking the positions of the tripped branches and studying the relationships between them and the topological characteristics of the power system blackout.

The outaged branches recorded in the BPA outage database are too disconnected to study if we try to form the network simply from the BPA data. Therefore we need to map the BPA branch outages to the corresponding branches of WECC to find their topological relationships. It is good that the WECC PSSE data offers the fundamental description of the whole WECC grid, and that BPA is a subset of the whole WECC grid, but, despite the owner codes in the WECC data, the institutional relationships are complicated and the details about the appropriate subgrid are not clear.

So the strategy is to find in the WECC grid the positions of BPA outaged branches and the non-outaged branches that connect them in the WECC grid. That is, we want to map the BPA outages branches into the WECC grid. Then the spread of the outages can be analyzed in the WECC grid.

Unfortunately, there are some difficulties for the reasons listed below:

1. In the BPA data, the outaged branch is identified by its initial and final bus names and the voltage level. But the bus names of BPA only partly correspond to the WECC bus names. How to find the corresponding buses in the WECC for the BPA buses? Is it only a character string matching problem? In fact, there are many buses that have the same label but different voltage levels in WECC. Also some buses share the same name and the same voltage level but are far from each other in the WECC graph. Hence, how to get the mapping function from the outages from BPA to WECC is absolutely not a easy task.

2. Even if a bus name of BPA cannot be found in WECC by itself, it seems reasonable to match the BPA branches to WECC ones by simultaneously matching the start and receiving bus names of BPA branches to WECC branches. However, the probability of a correct matching result is less than 15%. This low percentage implies that considering the matching of character strings is not at all sufficient. It is necessary to study the characteristic topological structure of WECC to find the patterns in its power system architecture. It is hard to find the patterns because of the complicated power network of the WECC.

3. Assuming that the BPA outaged branches can be mapped into WECC, is it wise to use the whole WECC networks to study the cascade spreading behavior? The answer is negative. Because BPA is a small part of the whole 16,000 bus WECC network, and only the outaged data of BPA is available, it is unwieldy to use the entire WECC network. But the border of BPA is unknown and how to select from WECC a suitable subgrid that contains the BPA grid becomes another awkward problem.

In conclusion, how to select from the WECC grid a subgrid containing BPA network and how to map the buses and branches of BPA into the WECC subgrid are the first two challenges for studying the spatial spreading of the cascade from the given data. The next section explains why the selection of the subgrid containing BPA is considered first.

2.3 The importance of finding a subgrid of WECC containing BPA

The problem of selecting from WECC network a subgrid containing BPA grid should be solved first for the following reasons:

1. There are some buses that share the same labels in the WECC data but belong to totally different geographic areas, which can cause huge difficulties for us to find the actual positions of the BPA outaged branches. The bus MIDWAY is a good example; it appears in multiple different places in WECC, sometimes in various places in BPA area, and one is in the state of Arizona, which is in the southern part of WECC and far away from BPA. Buses with the same name will confuse the matching algorithm. Therefore, cutting out at first an initial subgrid containing BPA named BPA_{WECC1} helps to mitigate the confusion.

2. Close examination of the WECC grid shows that the single outaged branches of BPA usually corresponds to several branches connected in series in WECC, which means that BPA and WECC use different naming rules to define transmission branches and this, to some extent, has created great difficulties for us to get the mapping from BPA to WECC. But BPA_{WECC1} will be taken as a reference to get the exact position for BPA outaged branches to find the matching ones in WECC.

3. Studying the WECC grid also shows two other problems:

   (a) Many WECC buses share the same label but turn out to be different voltage level buses;

   (b) Some buses in BPA have totally different names in WECC. Branches with such buses, as mentioned above, cannot be mapped to WECC by a character string matching algorithm.

4. As we known, the area of BPA is only a small part of the WECC, and it will be much more computationally expensive for the program to position and match the buses and branches of BPA outage data to the entire WECC grid than to the subgrid of WECC.

2.4 The steps of finding the subgrid of WECC containing BPA

2.4.1 Finding the possible districts of BPA

It is good to plot the graph of WECC shown in Fig. 2.1, based on the PSSE data of WECC. The border of BPA in Fig. 2.1 is totally unclear, so the first task is to figure out and deduce the broad outline of the BPA grid.

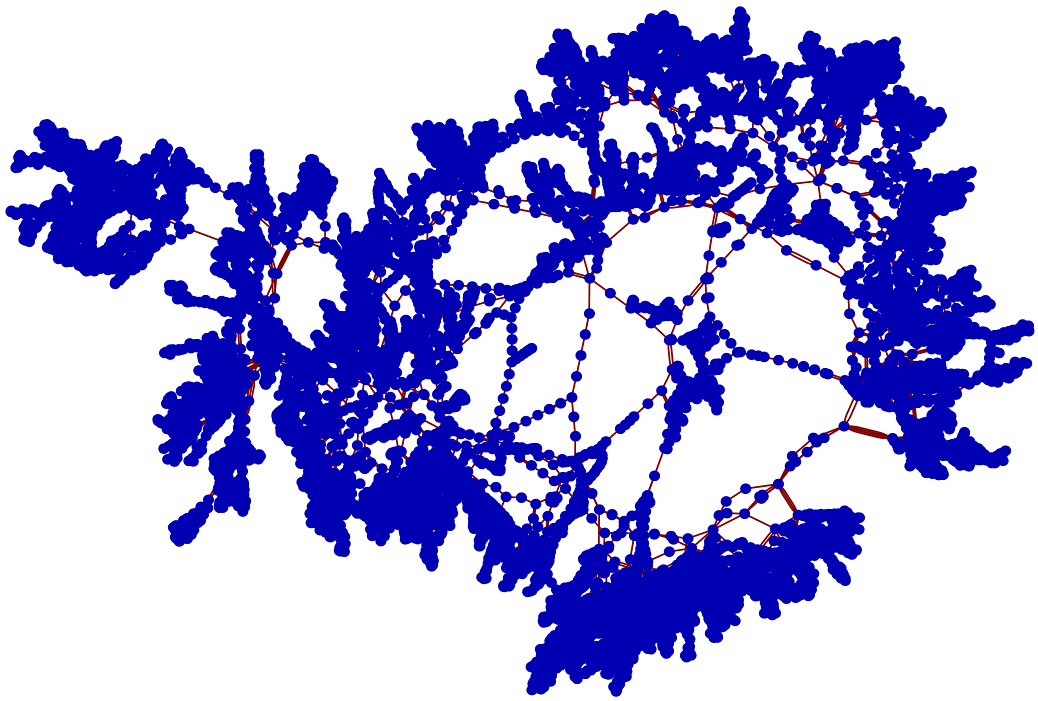

Figure 2.1 The graph of WECC

In view of the fact that the Bonneville Power Administration is mainly in charge of power transmission of Washington and Oregon states etc, and with studying the transmission branches in a map of principal transmission branches of WECC, it can be deduced that about ten districts in the map mainly construct the networks of BPA. By picking out all the branches and transformers of these corresponding areas in the WECC PSSE data, the first rough graph is shown in Fig. 2.2.

It is not strange that there are so many disconnected parts in Fig. 2.2, because the first subgrid only consider the areas we guessed but not the exact graph of BPA because this

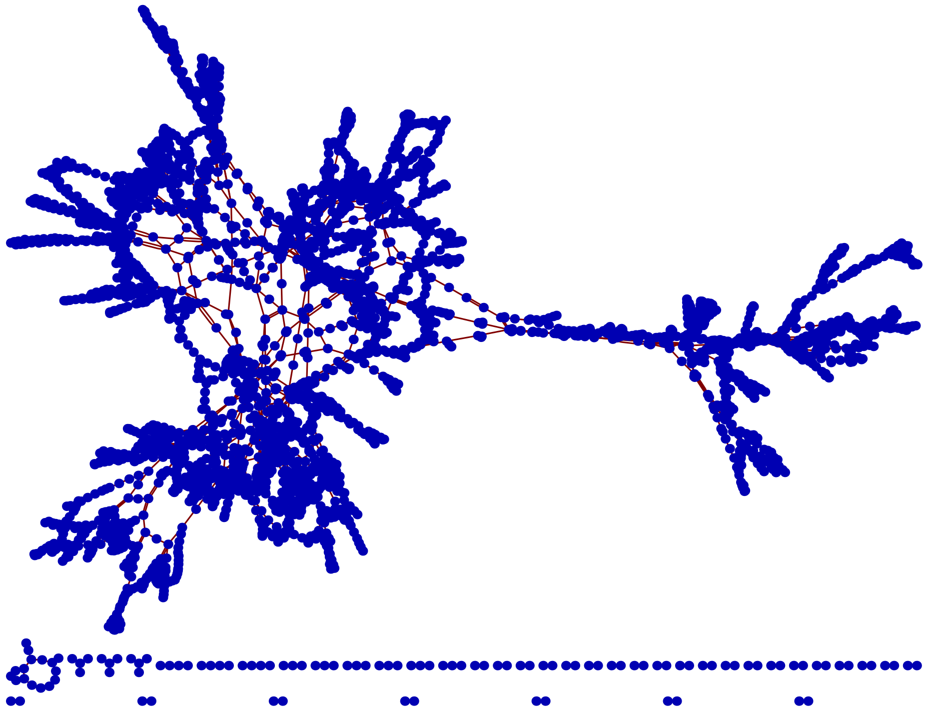

Figure 2.2 The first subgrid of WECC

information is unknown. How to find the branches connecting the disconnected parts of the subgrid becomes the next problem.

2.4.2 Find the possible branches connecting the first disconnected subgrid

2.4.2.1 Step 1

It is important to think that transformers are acting as bridges to transfer the power energy between voltage levels. Therefore, the transformers found in the first subgrid may not only connect with the branches we already got but also connect with the ones we are looking for.

According to this idea, we find all the transformers candidates which can connect the disconnected parts of Fig. 2.2, and then an updated graph is obtained, see Fig. 2.3. It is clear that in this second subgrid, only nine subgrid components are not connected with the biggest component.

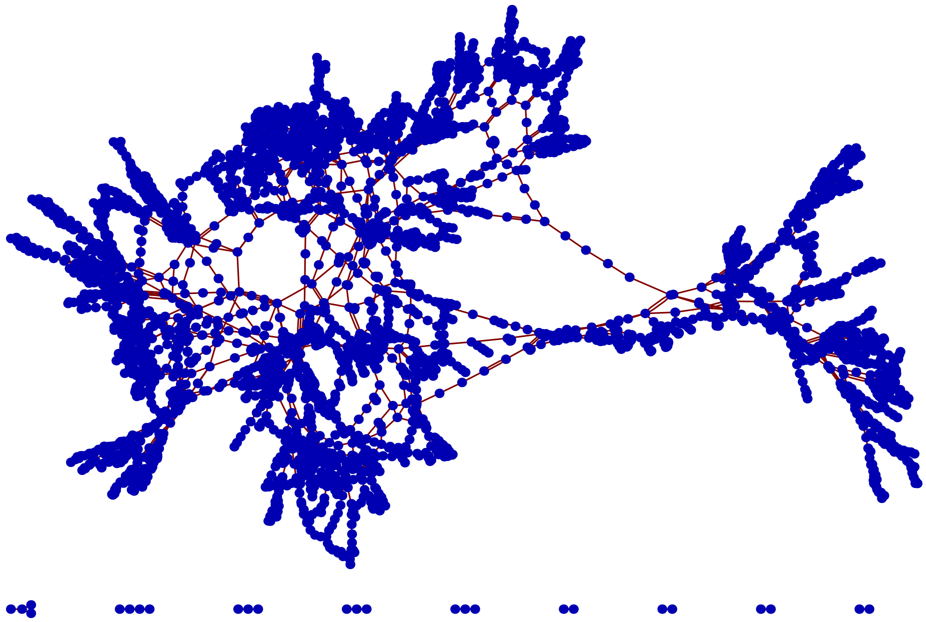

Figure 2.3 The second subgrid of WECC

The Fig. 2.3 shows that applying the transformer idea makes progress. But another interesting question appears, where do the nine disconnected parts come from?

2.4.2.2 Step 2

To answer the question in the end of last section, it is better to show the graph Fig. 2.3 in an alternative way as a colored graph with the colors chosen according to the different voltage levels of transmission branches and transformers, which helps us to understand the physical structure of WECC and find out where the nine disconnected parts come from. Then the branches which connected the nine subgrids with the main subgrid will be easier to be found manually in the WECC data. This final manual operation produces the subgrid BPA_{WECC1} shown in Fig. 2.4.

2.5 Conclusion

Following the previous steps, an approximate subgrid of WECC containing BPA is obtained successively.

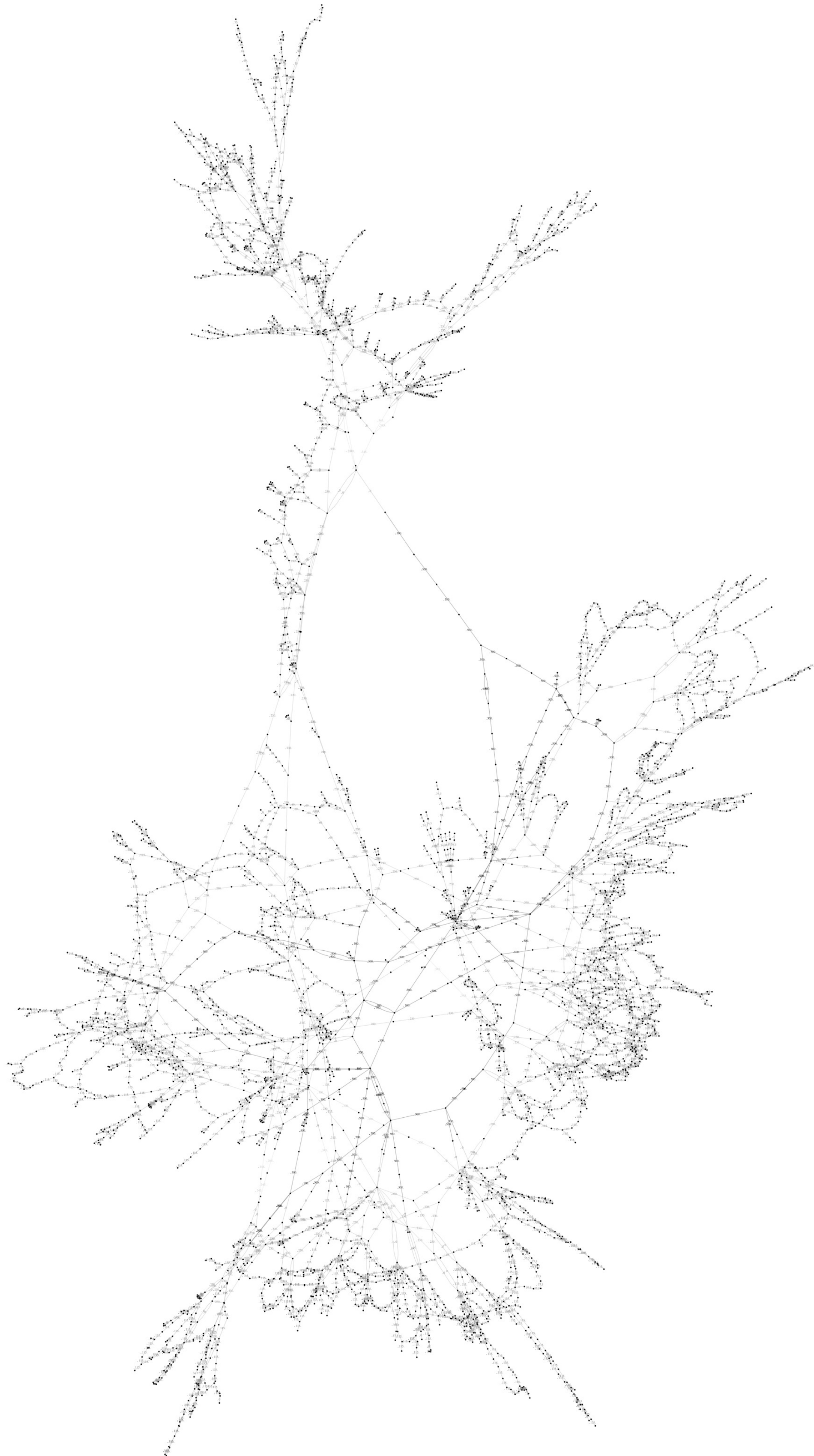

Figure 2.4 The final subgrid of BPA_{WECC1}

CHAPTER 3. MAPPING THE BPA OUTAGES INTO WECC GRID

3.1 Introduction

The previous chapter gives the steps to form the connected WECC subgrid BPA_{WECC1} that contains BPA grid. This chapter explains how to map the BPA outage branches into BPA_{WECC1}, and also to successively adjust the subgrid BPA_{WECC1} to turn it into a final subgrid G.

3.2 Steps before mapping BPA outage data to WECC

Since the bus names of outage branch data of BPA do not correspond well with the WECC grid data because of different name rules in WECC and BPA, the task of mapping the BPA outage data into BPA_{WECC1} seems challenging. Here are the steps to solve the problem:

Step 1. Match 20% of the outaged branches of BPA into BPA_{WECC1} by comparing these branches of BPA with the ones in BPA_{WECC1} by both the initial and final bus names. About 20% of the BPA outages can be positioned by this method.

Step 2. Position outaged branches of BPA by using bus name and voltage level to first locate a bus in BPA_{WECC1} corresponding to one end of the branch, say at bus A. Then grow a small subnetwork of BPA_{WECC1} starting from bus A of increasing maximum distance from bus A until a good enough match is found for the other end of the branch. Note that if bus A is connected to the other bus in BPA_{WECC1} via segments of branches, the subnetwork will grow along the line segments until bus B is reached. A further 75% of the BPA outages can be positioned by this method.

Step 3. Step 2 may not work if bus A is close to the edge of BPA_{WECC1}, because it may be necessary to grow the subnetwork to include branches outside BPA_{WECC1}. Therefore for step 3, follow the procedure of Step 2 but allow the subnetwork to grow in the full graph of WECC. Then, if a match is found for the other end of the branch, then record these matching branches and add them to BPA_{WECC1} to construct a new disconnected graph BPA_{WECC2} because the added branches are beyond the boundary of BPA_{WECC1}.

Step 4. Find the branches in the graph WECC to make the disconnected graph BPA_{WECC2} into the connected graph BPA_{WECC3}.

Step 5. Reduce the BPA_{WECC3} to BPA_{WECC4} by removing by inspection the buses in PSSE data which are the sections of transmission branches without load at these buses. The final graph BPA_{WECC4} is renamed as G for convenience.

3.3 Mapping Function

The final mapping function $f : BPA \to G$ maps more than 98% of the BPA outages into the subgrid G of WECC. This is sufficient to allow the spreading of the outages in G to be studied.

In G, there are approximately 3600 buses, 960 transformers, and 3600 transmission branches, among which there are 90 buses and 125 branches at 500 kV, about 40 buses and 50 branches at 345 kV, only a few buses and branches at 300 kV, approximately 470 buses and 580 branches at 230 kV, and approximately 3000 buses and 2890 branches below 230 kV at voltage levels such as 161 kV, 138 kV, 115 kV, 69 kV etc..[1] For this thesis, we are working with the outages of branches of 230 kV and above.

Now, all the matching processes of outage branches of BPA for the whole year of 2009 rated at 230 kV or above has been finished.

[1]The transmission branches rated 287kV in BPA correspond to the 300kV branches in BPA_{WECC4}.

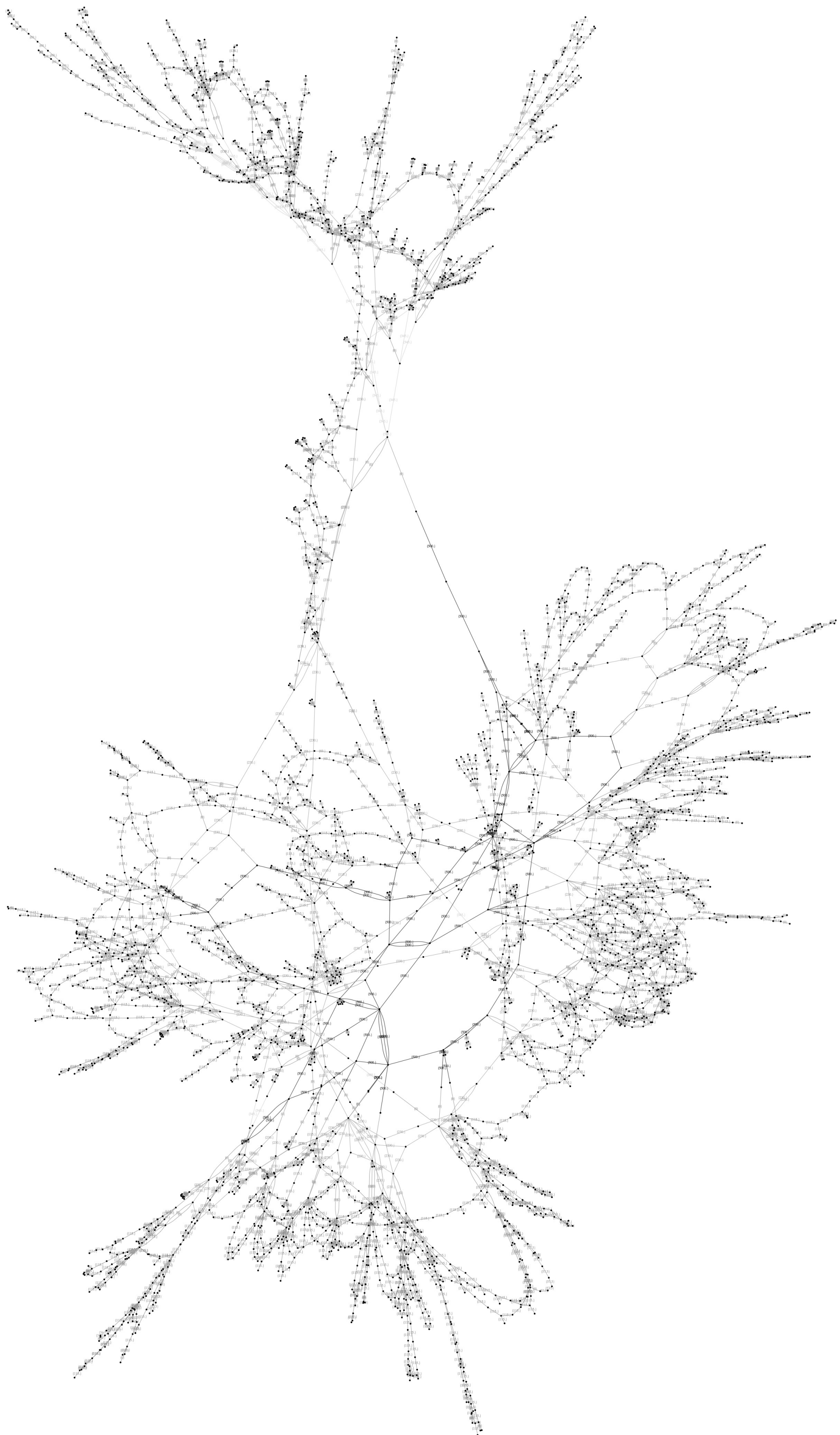

Figure 3.1 The graph of G, also called BPA_{WECC4}

CHAPTER 4. GROUPING OUTAGES INTO CASCADES AND GENERATIONS

4.1 Grouping outages into cascade and generations by timing

It is necessary to group the branch outages first into different cascades for analysis, and then into different generations within generations within each cascade. Here a simple method is used based on outages' timing [5, 6, 7]. Since operator actions are usually completed within one hour, successive outages separated in time by more than one hour are assumed to belong to different cascades. Since fast transients or auto-recloser actions are completed within one minute, successive outages in a given cascade separated in time by more than one minute are assumed to be in different generations within that cascade. The clustering of outages in generations can be seen in Fig. 4.1.

The result of this grouping of the outages into cascades and generations is that there are J=288 cascades. The data can be tabulated as follows, where $Z_k^{(j)}$ is the number of outages in generation k of cascade j:

Table 4.1 Cascades summarizing

	0	1	2	3	$\cdots$	sum over generations
cascade 1	$Z_0^{(1)}$	$Z_1^{(1)}$	$Z_2^{(1)}$	$Z_3^{(1)}$	$\cdots$	$Z^{(1)}$
cascade 2	$Z_0^{(2)}$	$Z_1^{(2)}$	$Z_2^{(2)}$	$Z_3^{(2)}$	$\cdots$	$Z^{(2)}$
cascade 3	$Z_0^{(3)}$	$Z_1^{(3)}$	$Z_2^{(3)}$	$Z_3^{(3)}$	$\cdots$	$Z^{(3)}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
cascade J	$Z_0^{(J)}$	$Z_1^{(J)}$	$Z_2^{(J)}$	$Z_3^{(J)}$	$\cdots$	$Z^{(J)}$
sum over cascades	Z_0	Z_1	Z_2	Z_3	$\cdots$	

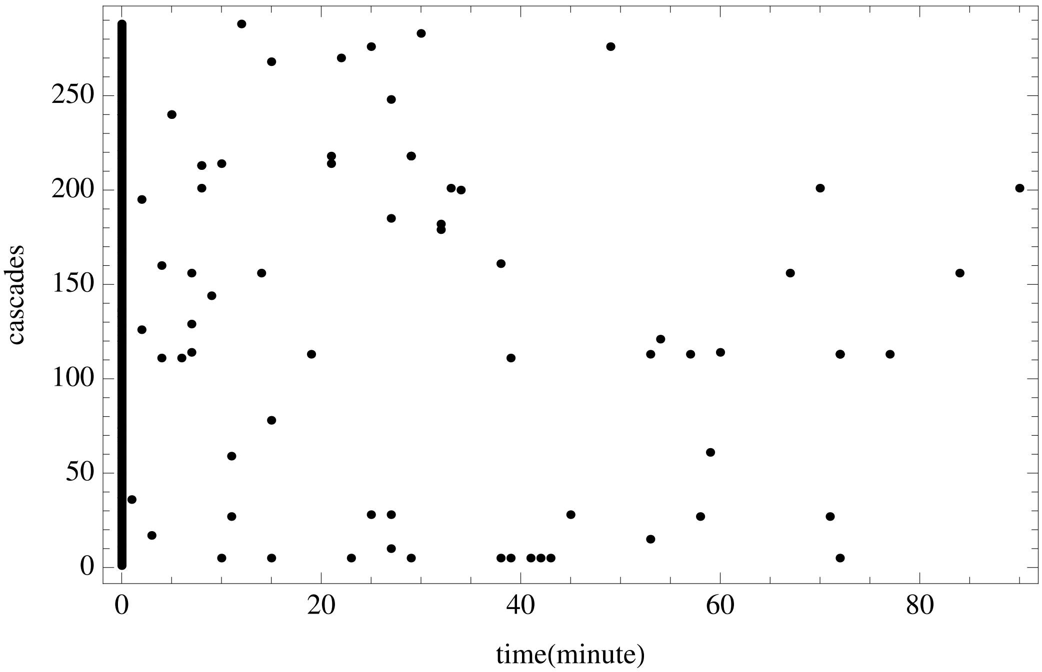

Figure 4.1 Times since start of cascade for outages in each of the 288 cascades.

Because of removing the outages that we do not study, there are altogether 393 outages whose voltage level are 230 kV or above that happened in the whole year of 2009; indeed only 76 branches tripped in 2009 because some branches repeatedly outage many times. The 76 branches produced 288 cascades, with 55 cascades' length longer than 1, which means that the other 233 cascades did not produce generations past the initial generation.

4.2 Grouping outages into cascade and generations into specific branches

By tracking the logged times of outaged branches in every generation and cascade, corresponding outaged branches can be gathered in both cascade and generation. This generations provide one foundation for calculating the distance between the generations among every cascade, the other one is the previously obtained mapping of BPA data into the network G.

To make the statement clearly, Table 4.2 shows the cascades and generations, where $G_k^{(j)}$ is the set of branches of outages in generation k of cascade j.[1]

For the corresponding 393 outages of the year of 2009, we ordered and labelled the 76 out-

[1]Here $G_k^{(j)}$ means grouping, which is different than the graph G defined above.

Table 4.2 Cascades BPA 2009

	0	1	2	$\cdots$	6	7
cascade 1	$G_0^{(1)}$	$G_1^{(1)}$	$G_2^{(1)}$	$\cdots$	$G_6^{(1)}$	$G_7^{(1)}$
cascade 2	$G_0^{(2)}$	$G_1^{(2)}$	$G_2^{(2)}$	$\cdots$	$G_6^{(2)}$	$G_7^{(2)}$
cascade 3	$G_0^{(3)}$	$G_1^{(3)}$	$G_2^{(3)}$	$\cdots$	$G_6^{(3)}$	$G_7^{(3)}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
cascade 288	$G_0^{(288)}$	$G_1^{(288)}$	$G_2^{(288)}$	$\cdots$	$G_6^{(288)}$	$G_7^{(288)}$

aged branches as L1, L2, . . . , L76. And Table 4.3 shows the detailed cascades and generations.

Table 4.3 Branches grouped by Cascades

	0	1	2	$\cdots$	6	7
cascade 1	L53					
cascade 2	L48					
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
cascade 5	L38	L20	L20	$\cdots$	L20,L38	L38
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
cascade 288	L38,L53					

CHAPTER 5. CASCADE DISTANCE AND SPREADING

To characterize cascade spreading, we need some notion of distance, and here we use graph topological distances.

5.1 Definition of graph distance

In graph theory, the distance $d_G(u, v)$ between two vertices u and v of a finite graph G is the number of edges in a minimum length path connecting them. And a graph's diameter $\max_{u,v} d_G(u, v)$ is the longest distance between any two graph vertices. In other words, a graph's diameter is the largest number of vertices which must be traversed in order to travel from one vertex to another when paths which backtrack, detour, or loop are excluded from consideration. In the graph of BPA_{WECC4}, the graph diameter is 50.

5.2 Definition of the distance between branches

Before giving the definition of the distance between the generations of cascade in the undirected graph G, the distance between branches should be defined. Assume the branches $L_i := \{v_{i_1}, v_{i_2}\}$, $L_j := \{v_{j_1}, v_{j_2}\}$; where v_{i_1} and v_{j_1} are the initial vertices of branches L_i, L_j, and v_{i_2} and v_{j_2} are the final vertices of branches L_i, L_j.

$$d_G(L_i, L_j) := \begin{cases} 1 & \text{if } \{v_{i_1}, v_{i_2}\} \cap \{v_{j_1}, v_{j_2}\} \text{ has one element} \\ 0 & \text{if } \{v_{i_1}, v_{i_2}\} \cap \{v_{j_1}, v_{j_2}\} \text{ has two elements} \\ n & \text{if } \{v_{i_1}, v_{i_2}\} \cap \{v_{j_1}, v_{j_2}\} \text{ has no elements} \end{cases}$$

where

$$
\begin{aligned}
n &= \min[d_G[(v_{i_1}, v_{i_2}) \times (v_{j_1}, v_{j_2})]] \\
&= \min[d_G(v_{i_1}, v_{j_1}), d_G(v_{i_1}, v_{j_2}), d_G(v_{i_2}, v_{j_1}), d_G(v_{i_2}, v_{j_2})]
\end{aligned}
\tag{5.1}
$$

5.3 Distances between cascade generations

First we define $C_k^{(j)}$ as the set of all possible combinations of successive outage pairs between generation $k-1$ and generation k in cascade j.

$$
C_k^{(j)} := \begin{cases} G_k^{(j)} & \text{if } k = 0 \\ \cup(G_{k-1}^{(j)}) \times \cup(G_k^{(j)}) & \text{if } k > 0 \end{cases}
\tag{5.2}
$$

Since $C_k^{(j)}$ is the combinations of all the possibilities of successive outage pairs, the combinations of all possible distances between outages in the successive generations are involved in the distance between the generations. Therefore, the definition of the distance between generations is not unique. We use $D^j_{min_k}$, $D^j_{max_k}$, $D^j_{mean_k}$ to define the minimum, maximum, and mean of the combination of distances between generations respectively. In other words, $D^j_{min_k}$, $D^j_{max_k}$, $D^j_{mean_k}$ are the minimal, maximal and average distance between generation as defined below:

$$
D^{(j)}_{min_k} := \begin{cases} 0 & \text{if } k = 0 \\ min[d_G(C_k^{(j)})] & \text{if } k > 0 \end{cases}
\tag{5.3}
$$

$$
D^{(j)}_{max_k} := \begin{cases} 0 & \text{if } k = 0 \\ max[d_G(C_k^{(j)})] & \text{if } k > 0 \end{cases}
\tag{5.4}
$$

$$
D^{(j)}_{mean_k} := \begin{cases} 0 & \text{if } k = 0 \\ mean[d_G(C_k^{(j)})] & \text{if } k > 0 \end{cases}
\tag{5.5}
$$

Now the spatial spreading between adjacent generations is discussed in all the 288 cascade using the mean distance between generations in Equation 5.5. There are mean distances between adjacent generations the same cascade of 0, 1, 2, 3, 4, 5, 6, 7, 9, 12, and 21 in the data set. An empirical estimate of the probability distribution of the mean distances is given by

$$p_{\text{adj}}[m] = \frac{\text{number of successive generations with mean distance } m}{\text{total number of successive generations}}$$
$$= \frac{1}{J} \sum_{j} \sum_{k \geq 1} I[D^{(j)}_{mean_k} = m] \quad (5.6)$$

where

$$J = \text{total number of successive generations}$$
$$= \sum_{j} \text{number of successive generations in cascade } j \quad (5.7)$$

and where the indicator function $I[\text{event}]$ evaluates to 1 if the event is true and evaluates to 0 if the event is false.

Based on equation 5.6, the empirical probability distribution of mean distance between successive generations is shown in Fig. 5.1.

The empirical probability distribution estimated with Equation 5.6 shown in Fig. 5.1 lacks

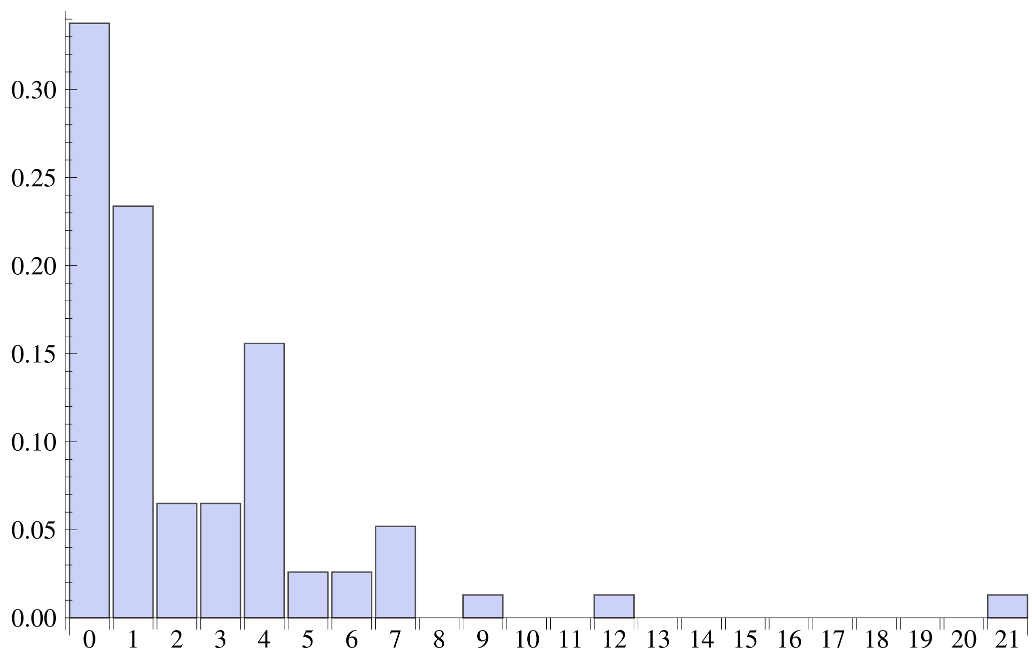

Figure 5.1 Barchart of the probability distribution of mean distance between successive generations.

accuracy because the number of successive generations $J = 77$ is too small for firm conclusions. The statistical accuracy is discussed in section 5.5. However, we proceed with a preliminary discussion of the results in the next section to show the kind of conclusions indicated by the results obtained so far.

5.4 Discussion of results A

Fig. 5.1 shows that the probability of one outage branche causing itself to outage in the next generation is as high as 34%, and the probability of it causing the adjacent branch outage in the next generation is 23%, the probability of spreading to the branches of the distance as far as 2 or 3 away is only 6%, but the probability of spreading to the branches of the distance as far as 4 away is as high as 16% and the probability of spreading to the branches of the distance as far as 7 away is, perhaps unexpectedly, 5%.

Therefore, the probability distribution of spatial spreading between adjacent generations is consistent with the idea that the cascading failure does not always spread to the adjacent branches. This idea may be natural for power system engineers, but it is hard for network scientists to accept.

Some possible reasons for the long distance spread are discussed:

1. Faults are classified by two types: the instantaneous fault and the permanent fault. In the normal situation, the instantaneous faults appear and are cleared soon, which will not cause the faulting branches to trip twice and therefore there is no fault spreading in the grid. For the permanent fault, faulting branch will be tripped again after re-closing because of permanent fault keeping and the protection has to clear and isolate the fault. However in some cases, control room will reclose the tripped branches after about half an hour assuming that the faults are disappeared, but because of weather like wind or lightning causing the faulting condition to still exist or reappear frequently, therefore the faulted branches will trip again within one cascade, which might be the reason that 34% of one outaged branches trip again in the next generation of a cascade.

2. Assume that overloading happen in the power grid, one branch will be tripped by relay, the topology of the grid will also change, and the power flow will redistribute along a cut set of branches. As a result, the next overloaded branch might not be the adjacent branch

because Zone-2 of distance relay acting as one of the primary protection of transmission branches has already isolated the fault and protected the fault from extending to the adjacent branches. In other words, one branch's tripping because of overloading does not mean the adjacent one will be exactly overloaded and trip successively. Indeed the smaller probability of the spreading between adjacent generations may show the intention of the relay to help the power system to operate in safety and reliability by isolating the faults other than propagating the faults, or cascading failure will spread to the adjacent branches successively.

Another aspect is that the hidden failure model considers that relay protection equipment might have to operate in abnormal situations and refuse transmitting tripping signal to the breaker to isolate the faulting branch. This hidden failure happens rarely, but the impact can be catastrophic [19]. In this case, the failure of the primary protection will cause the backup protection to trip the adjacent branch to avoid the spreading of the fault. However, sometimes because of the seriously overloading and no effective load shedding, the cascading effect has the potential to blackout a large area of power grid. For this issue, installing redundant relay recommended by NERC [21] is an effective method to decrease the possibility of refusal-operation of protection. In fact, redundant protection has been operated more than twenty years in Chinese power grid with the much weaker primary system compared with North America but much fewer blackouts. By installing redundant protection in the secondary system, the probability of refusal-operation of protection $p_{failure}$ will be decreased to $\frac{p_{failure}}{4}$, because both of the tripping coils of redundant replays are in parallel and the two contacts corresponding to them also are in parallel in another independent circuit, and with the incorporation of the two parts of the DC control circuit, the tripping signal can be transmitted to the breaker tripping coil to trip the faulting branch, and some failure of them will not cause refusal-operation of protection.

In conclusion, the cascading failure models in complex network theory that assume the spreading of overloading and cascading sequence to the adjacent branches as the mechanism to simulate the cascading failure in power systems should be corrected. At the same time, cascading model should not only consider the grid of the primary power system but also the protection configuration and settings to more accurately simulate cascading failure.

5.5 Statistical error in the distribution of spatial spreading between adjacent generations

The empirical probability estimator $p_{\text{adj}}[m]$ of mean successive generation distance m is estimated using equation 5.6. This section roughly estimates the statistical accuracy of the estimate $p_{\text{adj}}[m]$. The number of samples (number of successive generations in all the cascades) is $J = 77$.

The distribution of $J\, p_{\text{adj}}[m]$ is Binomial$(J, p_{\text{adj}}[m])$, and hence the standard deviation of $p_{\text{adj}}[m]$ is

$$\sigma(p_{\text{adj}}[m]) = \sqrt{\frac{p_{\text{adj}}[m](1 - p_{\text{adj}}[m])}{J}} \tag{5.8}$$

The standard deviation in the estimates is shown in Table 5.1. Also, as a rough approximation to a 95% confidence interval assuming normally distributed probability estimates, 1.96 standard deviations is also shown.

The individual estimates of $p_{\text{adj}}[m]$ are not sufficiently accurate for firm conclusions, especially for the larger m. This difficulty can be mitigated, but not satisfactorily eliminated, by estimating events that combine together several values of m as is done in section 5.4. The obvious solution is to process many more years of data. Indeed, we have 10 years of BPA outage data available. Processing 4 years of data would half the uncertainties of the estimates, and processing 10 years of data would divide the uncertainties by 3.3. These estimates of the uncertainty in estimating $p_{\text{adj}}[m]$, together with estimating events that combine together several values of m, strongly suggest the feasibility of statistically sound answers at the expense of processing more data.

The problem is that processing more data is at present very labor intensive and time consuming. It would also be desirable to extend the analysis to include at least one significant voltage level below 230 kV. We either need to invest about 6 to 12 months effort on this processing and/or find better ways to do the processing. This is a key element of future work.

Table 5.1 Statistical table about spatial spreading between adjacent generations

m	$p_{\text{adj}}[m]$	$\sigma(p_{\text{adj}}[m])$	$1.96\sigma(p_{\text{adj}}[m])$
0	0.338	0.054	0.106
1	0.234	0.048	0.095
2	0.065	0.028	0.055
3	0.065	0.028	0.055
4	0.156	0.041	0.081
5	0.026	0.018	0.036
6	0.026	0.018	0.036
7	0.052	0.025	0.050
9	0.013	0.013	0.025
12	0.013	0.013	0.025
21	0.013	0.013	0.025

5.6 A cumulative distance that a cascade has spread

Define $\mathscr{D}^{(j)}_{min}$, $\mathscr{D}^{(j)}_{max}$, $\mathscr{D}^{(j)}_{mean}$ as the the minimal, maximal and average cumulative spreading distance of cascade j respectively:

$$\mathscr{D}^{(j)}_{min} := \sum_{k=0}^{max[k]} D^{(j)}_{min_k} \tag{5.9}$$

$$\mathscr{D}^{(j)}_{min} := \sum_{k=0}^{max[k]} D^{(j)}_{max_k} \tag{5.10}$$

$$\mathscr{D}^{(j)}_{mean} := \sum_{k=0}^{max[k]} D^{(j)}_{mean_k} \tag{5.11}$$

These measures accumulate the distance moved in the graph for the entire cascade. Note that the cascade will not generally proceed in a straight line and that some of the distance may be incurred as the cascade doubles back near to some previous failures. Fig. 5.2 uses Equation 5.11 to show the average spatial spreading distribution of all the 288 cascades in the year of 2009 of BPA.

5.7 Discussion of results B

It seems that the Fig. 5.2 shows much fewer outages than Fig. 4.1; the reason is that certain different generations spread from the first generation to the same distance away in most of the

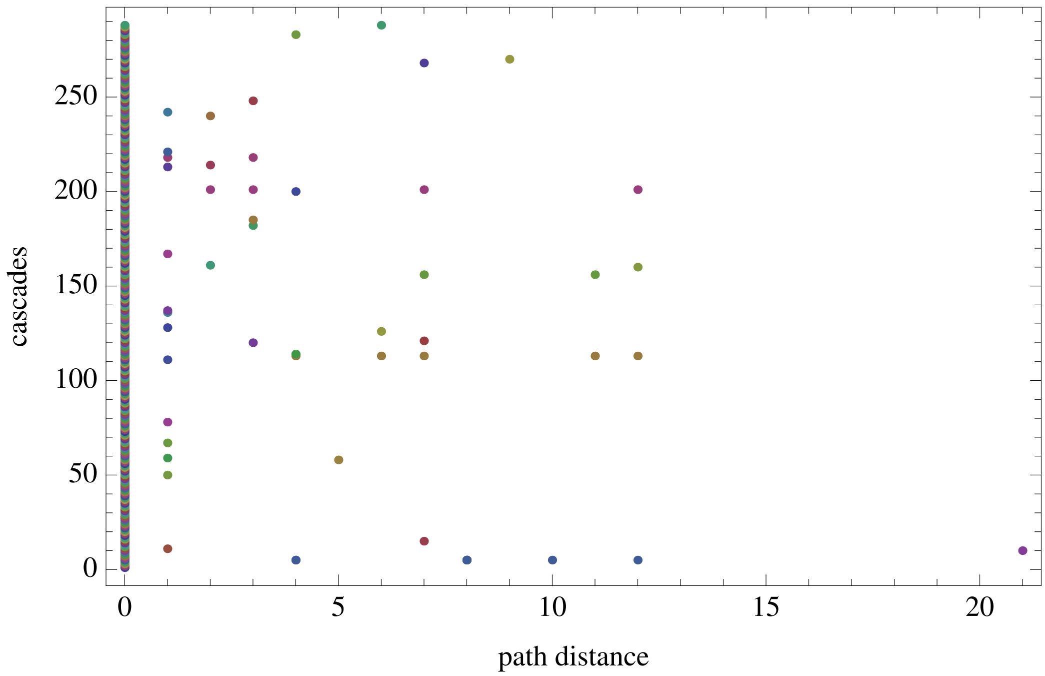

Figure 5.2 Average spatial spreading distribution of all the 288 cascades.

288 cascades, and therefore a lot of outages overlap in the dots shown in Fig. 5.2.

Comparing Fig. 5.2 with Fig. 4.1, a phenomenon can be found that the cascade 10 that spreads farthest in space is different than the cascade 5 that has the most generations, and both of them are not the cascade 201 that persists for the longest time 90 minutes. This result suggests two ideas towards the defense of cascading failure.

1. From the planning perspective: By studying the four cascades of the 288 cascades which spread farthest and with relatively more generations, all of the reasons are weather problems, which also explain why the blackout is usually reported in winter or summer. Therefore, for protecting the power grids from the weather disasters, the planning strategy should be updated not only to build an optimization problem with the objective function about investment and rewards with certain constraints about protecting ecology environment and limitation of emission of CO_2 etc, without considering the cascading failure and just using $N-1$ contingency to test the reliability of the result, but also need to add the proper cascading failure model to improve the results.

2. From the protection perspective: Current philosophies and technologies allow only local, narrowly focused, control actions based on measurements at the substation or branch level [**?**], which cannot prevent or reduce catastrophic failures and cascading sequences of events caused by various sources of vulnerability, otherwise Fig. 5.2 would tells us the different story that the spreading distances of cascading failure will stay at zero or not far away. Therefore the conception of Strategic Power Infrastructure Defense (SPID)[**?**] is really a promising strategy to defend against the cascading failure, and this conception is based on system-wide analysis. But how to define the width of particular power system? The preliminary study of the one year utility outage data tells us that the diameter of the graph G where all the outages branches in the year of 2009 can be mapped by function f is 50, while the farthest distance of the cascades can spread is to the branch with distance 21 away from the initial outage. This result gives us a clue to analyze from the observed data the required width of power system on which the wide-area protection system, which is the significant part of SPID, should be build on.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

There is a general need for the cascading failure analysis and simulation being developed in the power system, complex network, and optimization communities to be based on real power system data. In particular, since it is not feasible for general cascades to match every detail of cascades to observed cascades, it is useful to obtain an overall statistical description of cascading to which models and simulations can be compared. There is also a lack of detailed understanding of how cascades typically spread in blackouts. While many mechanisms for the spread have been suggested and simulated, and individual cascading sequences have been studied in detail, little is known about characterizing cascade spreading in general. It seems that being able to study the statistics of cascade spreading from real data is a good place to start to build a systematic understanding.

In this thesis, we develop methods to extract statistical data about the spreading of cascades. The primary challenge was being able to match or correlate TADS data that logs line outages to data describing the grid topology. We show how, with effort, this matching can be done on one year of data. More than 98% of the 2009 TADS line outages can be located on the grid topology.

We also initially explore some ways to characterize the cascade spreading with the distance on the graph between outages. A key result, expected in the field of power systems, but unexpected in the field of complex networks, is that a substantial fraction of line outages propagate to outages of other lines not adjacent in the network. This conclusion about observed cascading data is expected to bring into question many of the models for cascading used in the complex network field, in which outages exclusively propagate along the network. The results also show that lines quite often outage again more than a minute after their initial outage. We will investigate the mechanism for this in future work.

The statistical estimates of probabilities in the results are tentative because processing one year of outage does not give good enough resolution in the estimates. However, based on the results so far, 6 to 12 months more work processing data from 10 years of data will give reliable estimates. This, together with extending the analysis to below 230 kV, will be a major thrust of future work.

The ability to locate line outage data on the grid topology that we demonstrate in this thesis is also expected to open up a number of opportunities for analysis of cascading failure based on observed data. It will help in identifying the main mechanisms for propagation of failures, since spatial information can clarify or exclude possible mechanisms. The statistics of cascade spreading will not only provide a point of realistic comparison for existing cascading models and simulations, but also allow simple probabilistic models summarizing the spread to be constructed. The simple models of the spread, combined with the existing statistical models of cascading size, could be sampled to estimate the overall effect of initial failures when cascading is taken into account. It is of particular interest to estimate the likely range of cascading failure (the statistics of how far they spread from initial faults), since this governs the needed extent of wide area schemes to mitigate a large fraction of the cascades. It is also of interest to judge how often cascading is expected to cross institutional boundaries.

CHAPTER 7. CONTRIBUTIONS

In conclusion, my study has contributions listed below:

1. Solved the challenge of how to correlate two different data sources: real utility outage data and topology data, which opens the door to research on real electrical power grid in the complex network field.

2. Processing spreading data: Grouping the branches tripped in generations based on timing and the principle of protection system and using graph theory to define the spatial spreading between generations in a cascade.

3. Initial statistics of the spatial spreading of cascading failure in electric power system based on real outage data, which proves that the opinion insisted in the complex network field that cascading sequence always hop to the adjacent node is wrong in the real power system; and the cumulative distance that a cascade spread has the potential to help to defend against cascading failure and blackout.

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